1986

Development of the Relative Economic Weights for Linear and Quadratic Bioeconomic Objectives in Commercial Broilers

M. K. Akbar
Purdue University

D. L. Harris
Purdue University

C. R. Arboleda
Purdue University

Development of the Relative Economic Weights for Linear and Quadratic Bioeconomic Objectives in Commercial Broilers[1]

M. K. AKBAR[2], D. L. HARRIS[3], and C. R. ARBOLEDA[4]

Department of Animal Sciences, Purdue University

and

Animal Genetics Research Unit, ARS, USDA, West Lafayette, Indiana 47907

(Received for publication November 20, 1985)

ABSTRACT The approach of Harris (1970) and Harris *et al.* (1984) was used to develop mathematical profit functions for describing the bioeconomic objectives in an integrated three-way cross commercial broiler production system. The reproductive and productive performances of the pureline maternal grandparent female and the single cross female parent were included to reflect the impact of the traits expressed in those populations. The resulting complex function was approximated with linear and quadratic equations. Inputs (costs) in the system included feed, housing, labor and facilities, and processing. Outputs (returns) included salvage value of the cull hens and the processed cut-up broilers. A systematic procedure was developed to calculate relative economic values of the traits in the breeding objective from the bioeconomic function. The traits were boiler livability, boiler weight, proportion of carcass, proportion of breast-thigh-leg, broiler feed consumption, grower livability, layer livability, rate of lay, settability, fertility, and hatchability. The relative economic values thus obtained were 1.51, 1.00, 5.99, 3.21, −.20, 0, 0, 0, 0, 0, and 0 in paternal grandparent; 4.48, 1.00, 5.99, 3.21, −.20, 3.00, 3.10, 4.58, 2.97, 3.04 and 3.04 in maternal great-grandparent male; and 9.30, 1.00, 5.99, 3.21, −.20, 7.88, 8.15, 12.06, 7.80, 7.97, and 7.97 in maternal great-grandparent female, for the traits in the above order.

(*Key words:* bioeconomic objectives, economic weights, system analysis, broilers)

1986 Poultry Science 65:1834–1846

INTRODUCTION

Smith (1936) applied Fisher's (1936) concept of a discriminant function to construct an index for improving the net merit in plant varieties when selection criteria involved more than one trait. The theory of index construction was extended by Hazel (1943) to selection among individual animals. Construction of a selection index requries estimates of genetic and phenotypic parameters of the component traits and the relative economic values of the traits in the selection objective. The theory of estimating genetic and phenotypic parameters is well established (e.g., Becker, 1975), and many such estimates are available in the literature (e.g., Kinney, 1969) in poultry. However, procedures for developing relative economic values have not been very systematic, thus, reliable determinations of the economic weights in livestock are scarce.

Moav and Moav (1966) expressed a simple selection objective for a broiler operation with a profit function that included egg production of parents and growth rate of their progeny. Dickerson (1970) used the ratio of total cost to total return to reflect the bioeconomic efficiency in an animal system. However, the theoretical aspects and the statistical properties of a selection index, whose elements include ratios, are not well known and need to be further developed. Strain and Nordskog (1962) and Harris (1970) suggested that the bioeconomic objective in livestock species can be expressed by a function including the difference between total income and total cost and should include all the traits of economic importance and their related economic constants.

Hazel (1943) defined the linear selection objective in a linear index as the sum of the products of the additive genetic values of the

[1] Cooperative Project of Purdue University and USDA-ARS-MWA. Journal Paper No. 10465 of Purdue University.

[2] Present address: Peterson Industries, Decatur, AR 72722.

[3] Present address: Production Systems Research Unit, Roman L. Hruska US Meat Animal Research Center, Clay Center, NE 68933.

[4] Present address: Institute of Animal Science, University of Philippines at Los Banos, College, Laguna, The Philippines.

component traits and their economic weights. Wilton *et al.* (1968) extended Hazel's (1943) linear theory to a quadratic selection index for a quadratic objective. Hogesett and Nordskog (1958) presented a procedure to calculate the economic weights of the traits in farm animals from a direct market and farm price analysis. They defined the economic value of a trait as the amount of profit gained for every unit increase in that trait. Economic weights obtained by this procedure are influenced by the choice of the data collected and time and location of measurements. Linear economic weights can be approximated by regressing the net profit of the individuals on the component traits (Andrus and McGilliard, 1975). The partial regression coefficients obtained are suggested to be used as the economic weights. However, the procedure requires the development of a function to calculate net profit for each individual. Also, the economic weights will vary with the definition of profit, with the number of traits, and with the errors of estimates. Harris *et al.* (1984) presented a basis for systematically developing the economic weights directly from higher order functions describing the bioeconomic objective (net profit) in livestock species. Their approach depends upon the development of a mathematical formula for profit per individual production unit. The formula comprises traits of parents and offspring with coefficients involving fundamental economic constants such as price per unit weight of feed, market value of animals per unit weight, etc. Newman *et al.* (1985) applied this procedure to formulate a bioeconomic function for mice with implications for larger meat animals.

The objectives of this paper are: 1) to develop comprehensive mathematical profit functions for describing linear and quadratic bioeconomic objectives in an integrated three-way cross commercial broiler breeding system; and 2) to develop a method for calculating the relative economic values of the traits (linear) and products of the traits (quadratic) using the Harris *et al.* (1984) general procedure and to show numerical estimates for these parameters in commercial broilers.

General Structure of the System. Broiler traits deemed pertinent for inclusion in the bioeconomic objective were livability as proportion (BLV), live weight (WT) in pounds (454 g), dressed carcass as proportion of WT (DP), breast-thigh-leg as proportion of DP (BTL), and total unrestricted feed consumption (FD) in pounds (454 g). The grower trait was livability as proportion (GLV). Layer traits were livability as proportion (LLV), rate of lay in hen-day proportion (RL), settability as proportion of RL (ST), fertility as proportion of ST (FR), and hatchability as proportion of FR (HC). The fundamental economic constants and their assumed values for describing the bioeconomic objective of the system were: value of one pound (454 g) of breast-thigh-leg (v_{BTL}) = .90, value of one pound (454 g) remaining parts (v_{RP}) = .35, cost of one pound (454 g) broiler feed (c_{FD}) = .10, cost of labor and facility per broiler (c_{LF}) = .175, and cost of processing per broiler (c_{PR}) = .30. All prices and costs were in dollars.

The general structure of an integrated three-way cross broiler breeding operation and the flow in inputs and outputs in the system are diagrammed in Figures 1 and 2, respectively. Genetic groups are specified with letters (Fig. 1). The male parent (PM), maternal grandparent male (MGPM), and maternal grandparent female (MGPF) are genetically the same strains as paternal grandparent (PGP), maternal great-grandparent male (MGGPM), and maternal great-grandparent female (MGGPF), respectively, but they involve larger flocks. Males of MGPM and females of MGPF are crossed to produce the female parent (PF). Finally, males of PM and females of PF are crossed to produce the three-way cross commercial broiler (BR). In some commercial operations, an extra genera-

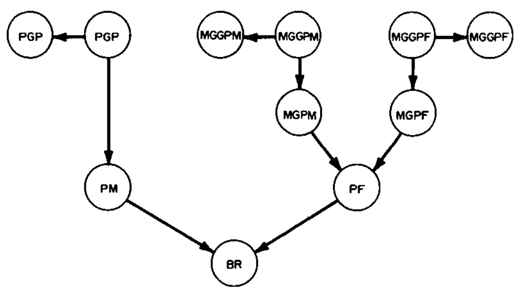

FIG. 1. Genetic groups in a three-way cross broiler breeding system. PGP, Paternal grandparent; MGGPM, maternal great-grandparent male; MGGPF, maternal great-grandparent female; MGPM, maternal grandparent male plus sibs of the opposite sex; MGPF, maternal grandparent female plus sibs of the opposite sex; PM, male parent plus sibs of the opposite sex; PF, two-way cross female parent; BR, three-way cross commercial broiler.

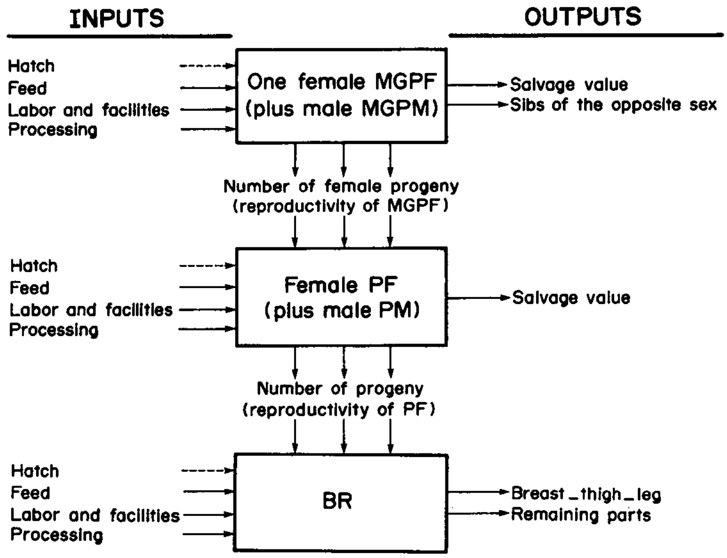

FIG. 2. Summary of the costs (INPUTS) and returns (OUTPUTS) in an integrated three-way cross commercial broiler production system. ⟶ Included in the bioeconomic function; ----→ Presumed to be of relatively minor impact, thus not included in the bioeconomic function.

tion exists between the great-grandparents and the grand parents for additional multiplication. This is not included in the considerations of this study.

Figure 2 is a summary of the costs (inputs) and returns (outputs) in the system. The PGP, MGGPM, and MGGPF lines are not shown in Figure 2, because they are genetically the same as the PM, MGPM, and MGPF, respectively. Reproductivity of the MGPF and PF may be obtained by the product of their reproductive traits. Costs of the initial breeding stocks are not included in Figure 2, because they occur in PGP, MGGPM, and MGGPF lines. Inputs relevant to the costs of the initial breeding stocks and hatching in an integrated system are presumed to be of relatively minor impact. These are not included in the construction of the bioeconomic functions to be used in the calculation of the relative economic weights. Further, it was presumed that the commercial broilers are marketed at a constant age; processed broilers are sold as breast-thigh-leg or remaining parts; processed culled hens are sold as whole carcass; and costs included feed, processing, and labor and facilities.

Formulation of the Bioeconomic Function. The fundamental production unit in the system is taken to be a single female MGPF and her descendants, including females PF and all their BR progenies (Fig. 1). A mathematical formula can be developed to describe profit per individual production unit. The formula is alternatively called the profit function or the bioeconomic function. Improvement of the profit function may be set as the bioeconomic objective of the system. The profit function (P) may be given by:

P = Net value of the total broilers produced by a female MGPF

= (Total number of broilers produced by a female MGPF × broiler performance) − net breeding cost (C)

= (Reproductivity in MGPF × reproductivity in PF × net value of a commercial broiler) − C

$$= R_{MGPF} \times R_{PF} \times V_{BR} - C \quad [1]$$

where R_{MGPF}, R_{PF}, and V_{BR} are reproductivity in MGPF, reproductivity in PF, and the net value of a commercial broiler, respectively. The term C is the net cost associated with a female MGPF and her two-way cross female progenies. In order to avoid excessive complexity, each segment of Equation [1] will be developed separately.

The net value of a commercial broiler (V_{BR}) may be given by:

$$V_{BR} = \text{Income per broiler} - \text{cost per broiler}$$

In a broiler operation, income and costs involve a complex function of the economic traits and their related economic constants. Based on the assumptions that were made, the above equation could be extended to:

$$V_{BR} = \text{(Amount of breast-thigh-leg)} \times \text{(unit price of breast-thigh-leg)} + \text{(amount of remaining parts)} \times \text{(unit price of remaining parts)} - \text{(Total broiler feed consumption)} \times \text{(unit cost of broiler feed)} - \text{(total cost of broiler labor and facilities from hatch to market age)} - \text{(total cost of broiler processing)}$$

$$= (BLV \times WT \times DP \times BTL)v_{BTL} + (BLV \times WT \times DP\,(1-BTL))v_{RP} - (BLV \times FD)c_{FD} - (BLV)c_{LF} - (BLV)c_{PR}$$

$$= (BLV \times WT \times DP)\,(BTL \times v_{BTL} + (1-BTL)v_{RP}) - BLV\,(FD \times c_{FD} + c_{LF} + c_{PR}) \quad [2]$$

In formulation of Equation [2], it was assumed that most of the broiler mortality occurred early in the broiler stage. Thus, no cost due to feed and labor and facilities was charged to the dead birds.

Each trait in Equation [2] can be expanded to a mean (μ_i) plus an additive deviation (δ_i).

$$V_{BR} = (\mu + \delta)_{BLV}\,(\mu + \delta)_{WT}\,(\mu + \delta)_{DP}\,((\mu + \delta)_{BTL}\ v_{BTL} + (1-(\mu + \delta)_{BTL})v_{RP}) - (\mu + \delta)_{BLV}\,((\mu + \delta)_{FD}\ c_{FD} + c_{LF} + c_{PR}). \quad [3]$$

Expansion and rearrangement of Equation [3] yield a complex function including terms with single δ values or products of two or more δ terms. Deletion of the terms with a product of three or more δ values in the process of expansion and rearrangement leaves a quadratic equation. Factorization and further simplification of this equation within the linear and the quadratic terms yield the quadratic function for the net value of a commercial broiler $v(_{BR(Q)})$.

$$V_{BR(Q)} = V'_{BR} + \sum_i X_i\delta_i + \sum_{i\leqslant j} X_{ij}\,\delta_i\delta_j \quad [4]$$

Deletion of the terms with a product of two or more δ values leaves a simpler linear approximation of the net value of a commercial broiler ($V_{BR(L)}$).

$$V_{BR(L)} = V'_{BR} + \sum_i X_i\delta_i \quad [5]$$

V'_{BR} in Equations [4] and [5] represents the mean productive performance of a BR. It is similar to V_{BR} (Equation [2]), but here it involves only the μ constants and does not include the δ terms.

$$V'_{BR} = (\mu_{BLV} \times \mu_{WT} \times \mu_{DP})\,(\mu_{BTL} \times V_{BTL} + (1-\mu_{BTL})V_{RP}) - \mu_{BLV}\,(\mu_{FD} \times c_{FD} + c_{LF} + c_{PR}) \quad [6]$$

Functions representing the X_i and X_{ij} coefficients of the δ_i and $\delta_i\delta_j$ terms (i,j = index for traits in the profit functions) in Equations [4] and [5] are presented in Table 1. The coefficients of the linear and the quadratic terms that do not occur in the profit functions are equal to zero. Because of the small magnitude of the δ values compared to the means (μ), their product terms are expected to be very small. Thus, the approximate linear and quadratic functions seem to be representative of the more complex higher order equation.

Reproductivity in MGPF (R_{MGPF} in Equation [1]) may be given by:

$$R_{MGPF} = \text{Total number of female chicks produced by a female MGPF in her production period}$$

$$= BLV \times GLV \times LLV \times RL \times ST \times FR \times HC \times d \times .5 \quad [7]$$

where, d = days in production/100 if RL is the hen-day percentage rate of lay, and d = days in production if RL is the hen-day proportion. Livabilities at broiler, grower, and layer stages are included in the function to reflect the probability that a female MGPF chick reaches and completes the egg production cycle. The coefficient .5 reflects the proportion of all chicks hatched that are female. Equation [7] may be written as:

$$R'_{MGPF} = (\mu + \delta)_{BLV}\,(\mu + \delta)_{GLV}\,(\mu + \delta)_{LLV}\,(\mu + \delta)_{RL}\,(\mu + \delta)_{ST}\,(\mu + \delta)_{FR}\,(\mu + \delta)_{HC}\ d \times .5 \quad [8]$$

TABLE 1. *Functions representing the coefficients of the quadratic and the linear terms in the profit functions for a commercial broiler (BR) (Equation [4] and [5])*[1]

Linear term[2] (δ_i)	Coefficient X_i
δ_{BLV}	$[(\mu_{WT}\,\mu_{DP})\,(v_{RP}(1-\mu_{BTL}) + \mu_{BTL}\,v_{BTL}) - (\mu_{FD}\,c_{FD} + c_{LF} + c_{PR})]$
δ_{WT}	$[(\mu_{BLV}\mu_{DP})\,(v_{RP}(1-\mu_{BTL}) + \mu_{BTL}\,v_{BTL})]$
δ_{DP}	$[(\mu_{BLV}\mu_{WT})\,(v_{RP}(1-\mu_{BTL}) + \mu_{BTL}\,v_{BTL})]$
δ_{BTL}	$[(\mu_{BLV}\,\mu_{WT}\,\mu_{DP})\,(v_{BTL} - v_{RP})]$
δ_{FD}	$-(\mu_{BLV}\,c_{FD})$
Quadratic term ($\delta_i\delta_j$)	**Coefficient X_{ij}**
$\delta_{BLV}\,\delta_{WT}$	$[(\mu_{DP}\,\mu_{BTL})\,(v_{BTL} - v_{RP}) + \mu_{DP}\,v_{RP})]$
$\delta_{BLV}\,\delta_{DP}$	$[(\mu_{WT}\,\mu_{BTL})\,(v_{BTL} - v_{RP}) + \mu_{WT}\,v_{RP})]$
$\delta_{BLV}\,\delta_{BTL}$	$[(\mu_{WT}\,\mu_{DP})\,(v_{BTL} - v_{RP})]$
$\delta_{BLV}\,\delta_{FD}$	$-(c_{FD})$
$\delta_{WT}\,\delta_{DP}$	$[(\mu_{BLV}\,\mu_{BTL})\,(v_{BTL} - v_{RP}) + \mu_{BLV}\,v_{RP})]$
$\delta_{WT}\,\delta_{BTL}$	$[(\mu_{BLV}\,\mu_{DP})\,(v_{BTL} - v_{RP})]$
$\delta_{DP}\,\delta_{BTL}$	$[(\mu_{BLV}\,\mu_{WT})\,(v_{BTL} - v_{RP})]$

[1] The coefficients of the linear and the quadratic terms that do not occur in the profit functions are equal to zero.

[2] BLV = Broiler livability as proportion, WT = live weight in pounds, DP = dressed carcass as proportion of WT, BTL = breast-thigh-leg as proportion of DP, FD = total unrestricted feed consumption.

Expansion, rearrangement, and simplification of Equation [8] and deletion of the higher order terms, similar to that of Equation [3], yield quadratic ($R_{MGPF(Q)}$) and linear ($R_{MGPF(L)}$) functions for reproductivity in MGPF.

$$R_{MGPF(Q)} = R'_{MGPF} + .5\ d\ \sum_k Y_k\delta_k + .5\ d \sum_{k\leq m} Y_{km}\,\delta_k\delta_m \qquad [9]$$

$$R_{MGPF(L)} = R'_{MGPF} + .5\ d\ \sum_k Y_k\delta_k \qquad [10]$$

The R'_{MGPF} in Equations [9] and [10] is the mean reproductive performance of a MGPF. It is similar to R_{MGPF} (Equation [7]), but here it involves only the μ constants and does not include the δ terms.

$$R'_{MGPF} = \mu_{BLV} \times \mu_{GLV} \times \mu_{LLV} \times \mu_{RL} \times \mu_{ST} \times \mu_{FR} \times \mu_{HC} \times d \times .5 \qquad [11]$$

Functions representing the Y_k and Y_{km} coefficients of the δ_k and $\delta_k\delta_m$ terms (k,m = index for traits in the reproductive functions) in Equations [9] and [10] are presented in Table 2. The coefficients of the linear and the quadratic terms that do not occur in the reproductive functions are equal to zero. Equations for quadratic and linear reproductive functions and for the mean reproductive performance in PF ($R_{PF(Q)}$, $R_{PF(L)}$ and R'_{PF}) are similar to those in MGPF (Equations [9], [10], and [11], respectively), except that the coefficient .5 should be removed from the equations, since both male and female progenies of the two-way cross PF are utilized as commerical broilers. Also, means (μ) for the PF population should be used.

Equation [1] now can be reconstructed as:

$$P_Q = R_{MGPF(Q)} \times R_{PF(Q)} \times V_{BR(Q)} - C \qquad [12]$$

$$P_L = R_{MGPF(L)} \times R_{PF(L)} \times V_{BR(L)} - C \qquad [13]$$

where P_Q and P_L are quadratic and linear profit functions. The net breeding cost (C) may be calculated as:

$$C = (1 + R_{MGPF})c_{LH} - (1 + R_{MGPF})v_{LH} - (R_{MGPF} \times V_{BS}) \qquad [14]$$

TABLE 2. *Functions representing the coefficients of the quadratic and the linear terms in the reproductive functions for a maternal grandparent female (MGPF) (Equations [9] and [10])*[1]

Linear term[2] (δ_i)	Coefficient (Y_k)	Quadratic term, (continued)	Coefficient, (continued)
δ_{BLV}	$.5d\,(\mu_{GLV}\,\mu_{LLV}\,\mu_{RL}\,\mu_{ST}\,\mu_{FR}\,\mu_{HC})$	$\delta_{GLV}\,\delta_{RL}$	$.5d\,(\mu_{BLV}\,\mu_{LLV}\,\mu_{ST}\,\mu_{FR}\,\mu_{HC})$
δ_{GLV}	$.5d\,(\mu_{BLV}\,\mu_{LLV}\,\mu_{RL}\,\mu_{ST}\,\mu_{FR}\,\mu_{HC})$	$\delta_{GLV}\,\delta_{ST}$	$.5d\,(\mu_{BLV}\,\mu_{LLV}\,\mu_{RL}\,\mu_{FR}\,\mu_{HC})$
δ_{LLV}	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{RL}\,\mu_{ST}\,\mu_{FR}\,\mu_{HC})$	$\delta_{GLV}\,\delta_{FR}$	$.5d\,(\mu_{BLV}\,\mu_{LLV}\,\mu_{RL}\,\mu_{ST}\,\mu_{HC})$
δ_{RL}	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{LLV}\,\mu_{ST}\,\mu_{FR}\,\mu_{HC})$	$\delta_{GLV}\,\delta_{HC}$	$.5d\,(\mu_{BLV}\,\mu_{LLV}\,\mu_{RL}\,\mu_{ST}\,\mu_{FR})$
δ_{ST}	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{LLV}\,\mu_{RL}\,\mu_{FR}\,\mu_{HC})$	$\delta_{LLV}\,\delta_{RL}$	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{ST}\,\mu_{FR}\,\mu_{HC})$
δ_{FR}	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{LLV}\,\mu_{RL}\,\mu_{ST}\,\mu_{HC})$	$\delta_{LLV}\,\delta_{ST}$	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{RL}\,\mu_{FR}\,\mu_{HC})$
δ_{HC}	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{LLV}\,\mu_{RL}\,\mu_{ST}\,\mu_{FR})$	$\delta_{LLV}\,\delta_{FR}$	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{RL}\,\mu_{ST}\,\mu_{HC})$
Quadratic term ($\delta_i\delta_j$)	Coefficient (Y_{km})	$\delta_{LLV}\,\delta_{HC}$	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{RL}\,\mu_{ST}\,\mu_{FR})$
$\delta_{BLV}\,\delta_{GLV}$	$.5d\,(\mu_{LLV}\,\mu_{RL}\,\mu_{ST}\,\mu_{FR}\,\mu_{HC})$	$\delta_{RL}\,\delta_{ST}$	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{LLV}\,\mu_{FR}\,\mu_{HC})$
$\delta_{BLV}\,\delta_{LLV}$	$.5d\,(\mu_{GLV}\mu_{RL}\mu_{ST}\mu_{FR}\mu_{HC})$	$\delta_{RL}\,\delta_{FR}$	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{LLV}\,\mu_{ST}\,\mu_{HC})$
$\delta_{BLV}\,\delta_{RL}$	$.5d\,(\mu_{GLV}\mu_{LLV}\mu_{ST}\mu_{FR}\mu_{HC})$	$\delta_{RL}\,\delta_{HC}$	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{LLV}\,\mu_{ST}\,\mu_{FR})$
$\delta_{BLV}\,\delta_{ST}$	$.5d\,(\mu_{GLV}\,\mu_{LLV}\,\mu_{RL}\,\mu_{FR}\,\mu_{HC})$	$\delta_{ST}\,\delta_{FR}$	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{LLV}\,\mu_{RL}\,\mu_{HC})$
$\delta_{BLV}\,\delta_{FR}$	$.5d\,(\mu_{GLV}\,\mu_{LLV}\,\mu_{RL}\,\mu_{ST}\,\mu_{HC})$	$\delta_{ST}\,\delta_{HC}$	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{LLV}\,\mu_{RL}\,\mu_{FR})$
$\delta_{BLV}\,\delta_{HC}$	$.5d\,(\mu_{GLV}\,\mu_{LLV}\,\mu_{RL}\,\mu_{ST}\,\mu_{FR})$	$\delta_{FR}\,\delta_{HC}$	$.5d\,(\mu_{BLV}\,\mu_{GLV}\,\mu_{LLV}\,\mu_{RL}\,\mu_{ST})$
$\delta_{GLV}\,\delta_{LLV}$	$.5d\,(\mu_{BLV}\,\mu_{RL}\,\mu_{ST}\,\mu_{FR}\,\mu_{HC})$		

[1] The coefficients of the linear and the quadratic terms that do not occur in the profit functions are equal to zero.

[2] BLV = Broiler livability as proportion, GLV = grower livability as proportion, LLV = layer livability as proportion, RL = rate of lay in hen-day proportion, ST = settability as proportion of RL, FR = fertility as proportion of ST, HC = hatchability as proportion of FR.

where V_{BS} is the value of a broiler sib (sib to PF female). R_{MGPF} and V_{BS} in Equation [14] may be in quadratic or linear forms. The terms c_{LH} and v_{LH} are costs (feed, labor and facilities, and processing) and values (processed culled hen) in dollars for one MGPF or one PF. They are calculated as follows:

$$c_{LH} = (rbf + rgf + rlf) + (blf + glf + llf) + c_{LPR} \quad [15]$$

$$v_{LH} = \mu_{LBW} \times \mu_{LDP} \times v_{LCR} \quad [16]$$

where rbf, rgf, and rlf are total costs of restricted feed at broiler, grower, and layer stages; blf, glf, and llf are total costs of labor and facilities at broiler, grower, and layer stages; and c_{LPR} is the cost of processing a cull hen. All the above costs were assumed to be constant. The terms μ_{LBW}, μ_{LDP}, and v_{LCR} in Equation [16] are body weight, dressing proportion, and value of 1-lb (454-g) carcass in cull hens, respectively, with all assumed constants. Broiler, grower, and layer stages were taken to be 0 to 7 weeks, 8 to 22 weeks, and 23 to 74 weeks, respectively. Other systems could be addressed with appropriate modifications of the economic values. Thus, $(1 + R_{MGPF})c_{LH}$ and $(1 + R_{MGPF})v_{LH}$ are total costs and total returns in dollars, for one average MGPF and all her female progenies from hatch to cull. $R_{MGPF} \times V_{BS}$ is the net value of the male progenies of the MGPF (sibs to PF females) sold as broilers. Quadratic and linear profit functions for V_{BS} are similar to those in V_{BR} (Equations [4] and [5]), but means from the PF population should be used.

Replacement of the net breeding costs (C) in Equations [12] and [13] with Equation [14] and further simplification of the resulting equations result in the complex profit functions in quadratic and linear forms, as follows:

$$P_Q = R_{MGPF(Q)} \times R_{PF(Q)} \times V_{BR(Q)} + R_{MGPF(Q)} \times V_{BS(Q)} + R_{MGPF(Q)} (v_{LH} - c_{LH}) \quad [17]$$

$$P_L = R_{MGPF(L)} \times R_{PF(L)} \times V_{BR(L)} + R_{MGPF(L)} \times V_{BS(L)} + R_{MGPF(L)} (v_{LH} - c_{LH}) \quad [18]$$

The constant term $(v_{LH} - c_{LH})$ is deleted from Equations [17] and [18] in the process of simplification. These equations may be further simplified by expansion, rearrangement, and factorization of their elements, and deletion of the higher order terms, similar to those of Equations [3] and [8].

Development of the Relative Economic Weights from the Bioeconomic Functions. Hazel (1943) defined the linear selection objective (net merit) in a linear index as:

$$H = a_1 g_1 + a_2 g_2 + \ldots\ldots\ldots a_k g_k$$

where a_i and g_i are relative economic and additive genetic values of the i^{th} trait (i = 1, 2, . . . k) in the net merit. Wilton *et al.* (1968) developed a quadratic selection objective for a quadratic index as:

$$M = a_1 g_1 + a_2 g_2 + \ldots\ldots\ldots a_k g_k + (A_{12} + A_{21})g_1 g_2 + (A_{13} + A_{31})g_1 g_3 + \ldots\ldots\ldots (A_{k-1\ k} + A_{k\ k-1}) g_{k-1} g_k + A_{11} g_1^2 + A_{22} g_2^2 + \ldots\ldots\ldots A_{kk} g_k^2$$

where A_{ij} (i,j = 1, 2, . . .k) are elements of the k × k symmetric matrix of the quadratic economic weights (A). The terms linear bioeconomic function (P_L) and additive deviation (δ_i) are synonomous with linear selection objective (H) and additive genetic value (g_i) of Hazel (1943). Similarly, the term quadratic profit function (P_Q) is synonymous with quadratic selection objective (M) of Wilton *et al.* (1968).

Harris *et al.* (1984) noted that the coefficient of the i^{th} additive deviation term in the linear profit equation is composed of a linear function of the mathematical products of one or more means for traits other than the i^{th} trait and the economic constants. Thus, it reflects the economic importance of the changes in that trait and can be considered the i^{th} economic weight of Hazel (1943). With the same methodology, the coefficient of the ij^{th} additive deviation term in the quadratic profit function reflects the economic importance of the changes in the quadratic (product) effect of those traits, thus can be considered the $(A_{ij} + A_{ji})$ economic weight of Wilton *et al.* (1968).

In livestock enterprise involving a species with high reproductive rate (e.g., poultry), most individuals in the system are production animals. Therefore, it might be accurate to assume that in a broiler-breeding operation, the quadratic and the linear functions for the net value of a commercial broiler ($V_{BR(Q)}$ and $V_{BR(L)}$ from Equations [4] and [5]) approximate adequately the more comprehensive quadratic and linear profit functions for the larger production unit (P_Q and P_L from Equations [17]

TABLE 3. *Phenotypic means in PGP, MGGPM, and MGGPF as the mathematical averages of the two sexes and in PF and BR with single-cross and double-cross heterosis factors of 1 and .06%*[1]

Trait[3]	Genetic group[2]				
	PGP	MGGPM	MGGPF	PF	BR
BLV	.92	.93	.93	.94	.94
WT	4.27	3.99	3.89	3.98	4.15
DP	.685	.685	.685	.693	.693
BTL	.65	.65	.65	.657	.657
FD	8.92	8.34	8.33	8.43	8.73
GLV	.91	.92	.92	.93	...
LLV	.88	.89	.89	.90	...
RL	.58	.60	.60	.61	...
ST	.93	.93	.93	.94	...
FR	.90	.91	.91	.92	...
HC	.90	.91	.91	.92	...

[1] From Harris *et al.* (1985).

[2] PGP = Parental grandparent, MGGPM = maternal great-grandparent male, MGGPF = maternal great-grandparent female, PF = two-way cross female parent, BR = three-way cross commercial broiler.

[3] BLV = Broiler livability as proportion, WT = broiler weight in pounds (454 g), DP = dressed carcass as proportion of broiler weight, BTL = breast-thigh-leg as proportion of carcass, FD = broiler feed consumption in pounds (454 g), GLV = grower livability as proportion, LLV = layer livability as proportion, RL = rate of lay in hen-day proportion, ST = settability as proportion of eggs laid, FR = fertility as proportion of settable eggs, HC = hatchability as porportion of fertile eggs.

and [18]). Thus, maximization of the profitability of an individual broiler might be set as the bioeconomic objective of the system. Under this circumstance, the matrix of quadratic and the vector of linear economic weights (A and a) may be obtained from Equations [4] and [5], respectively. For the calculation of the economic weights, the constant term V'_{BR} may be removed from these equations. These are shown in Table 4, using means of the traits in genetic group BR from Table 3 and the economic constants that were assumed. In the symmetric Matrix A, the square terms and the A_{ij} elements that do not occur in the quadratic function $V_{BR(Q)}$ are zero. Other A_{ij} and A_{ji} elements are calculated as half the value of the coefficient of $\delta_i\delta_j$ in the quadratic function.

The coefficients of the linear and the quadratic terms in the linear and the quadratic functions chosen as the economic weights are functions of the products of the phenotypic means and the economic constants. Therefore, changes in the phenotypic means, due to genetic selection, and in the economic con-

TABLE 4. *Matrix of quadratic (A) and vector of linear (a) economic weights from quadratic and linear functions for the net value of a commerical broiler*

Trait[1]	A					a
	BLV	WT	DP	BTL	FD	
BLV	0	.247	1.476	.790	−.050	.698
WT	.247	0	.335	.179	0	.463
DP	1.476	.335	0	1.073	0	2.775
BTL	.790	.179	1.073	0	0	1.487
FD	−.050	0	0	0	0	−.094

[1] BLV = Broiler livability as proportion, WT = broiler weight in pounds (454 g), DP = dressed carcass as proportion of broiler weight, BTL = breast-thigh-leg as proportion of carcass, FD = broiler feed consumption in pounds (454 g).

stants, due to price and market fluctuations, result in changes in the relative economic values of the traits. For example, if genetic selection for early growth rate in the foundation stocks results in a per generation phenotypic increase of .065 in WT, .0133 in FD, and no change in BLV, DP, and BTL in commercial broilers for 12 generations (from Harris, Akbar and Arboleda, 1985), the relative economic values of the traits from Equation [5] change as shown in Table 5. Economic weights for DP, BLV, and BTL were increased by a rate of .044, .031, and .023 dollars per unit of measurement per generation. Economic values of WT and FD did not change. Values in Table 5 do not reflect major changes in the economic constants during the 12 years of selection.

In the procedure outlined above, the profitability of the commerical unit was assumed to be representative of the profitability of the total integrated system. Therefore, the relative economic values were directly obtained from the functions describing the profitability of the three-way cross broilers. The assumption was made based on the recognition that, in poultry, with a high reproductive rate, most of the individuals in the system are commercial broilers. In livestock, with lower reproductive rates, reproduction of parents and grandparents play a greater role in the bioeconomic efficiency of the system. Therefore, the additional complexity from the inclusion of the reproductive traits for increasing the accuracy of the profit functions in describing the bioeconomic objectives of the system may have greater merit and justification in larger livestock.

Estimation of the Economic Weights in the Foundation Stocks. In a commercial broiler operation, directional selection is usually practiced only in PGP, MGGPM, and MGGPF foundation stocks. A systematic procedure was developed to obtain estimates of the quadratic and the linear economic weights in these lines from the quadratic and the linear profit functions (Equations [17] and [18]) and their biometrical relationship with the genetic groups included in the fundamental production unit. The reproductive and productive performances of the single-cross PF and the pureline MGPF were included to reflect the impact of those traits.

Because of the genetic composition of the crosses, the following relationships exist.

TABLE 5. *Change in the phenotypic means*[1] ($\overline{X}$) *and the economic weights*[2] (a) *in commercial broilers over twelve generations of selection in the foundation stocks*

Trait[3]	Year 0		Year 3		Year 6		Year 9		Year 12	
	$\overline{X}$	a	$\overline{X}$	a	$\overline{X}$	a	$\overline{X}$	a	$\overline{X}$	a
BLV	.94	.698	.94	.792	.94	.882	.94	.977	.94	1.066
WT	4.15	.463	4.35	.463	4.54	.463	4.74	.463	4.93	.463
DP	.693	2.775	.693	2.909	.693	3.036	.693	3.169	.693	3.297
BTL	.657	1.487	.657	1.558	.657	1.627	.657	1.698	.657	1.766
FD	8.73	−.094	8.77	−.094	8.81	−.094	8.85	−.094	8.89	−.094

[1] Per generation phenotypic increase of .00008 in broler livability as proportion, .065 in live weight, .0133 in total unrestricted feed consumption, and no change in dressed carcass and breast-thigh-leg were assumed (from Harris *et al.*, 1985).

[2] From the linear function of the net value of a commercial broiler (Equation [5]).

[3] BLV = Broiler livability as proportion, WT = broiler weight in pounds (454 g), DP = dressed carcass as proportion of broiler weight, BTL = breast-thigh-leg as proportion of carcass, FD = broiler feed consumption in pounds (454 g).

$$R_{MGPF} = R_{MGGPF}$$

$$RPF = .5\, R_{MGGPM} + .5\, R_{MGGPF} + \text{heterosis}$$

$$V_{BR} = .5\, V_{PGP} + .25\, V_{MGGPM} + .25\, V_{MGGPM} + .25\, V_{MGGPF} + \text{heterosis}$$

$$V_{BS} = .5\, V_{MGGPM} + .5\, V_{MGGPF} + \text{heterosis}$$

The quadratic and the linear approximations of the profit equation as the function of the characteristics of the three foundation stocks are obtained by substituting these into Equations [17] and [18] and dropping the constant heterosis terms.

$$P_Q = R_{MGGPF(Q)}\,((.5\, R_{MGGPM(Q)} + .5\, R_{MGGPF(Q)})\,(.5\, V_{PGP(Q)} + .25\, V_{MGGPM(Q)} + .25\, V_{MGGPF(Q)}) + (.5\, V_{MGGPM(Q)} + .5\, V_{MGGPF(Q)}) + (v_{LH} - c_{LH})) \quad [19]$$

$$R_L = R_{MGGPF(L)}\,((.5\, R_{MGGPM(L)} + .5\, R_{MGGPF(L)})\,(.5\, V_{PGP(L)} + .25\, V_{MGGPM(L)} + .25\, V_{MGGPF(L)} + (.5\, V_{MGGPM(L)} + .5\, V_{MGGPF(L)}) + (v_{LH} - c_{LH})) \quad [20]$$

The linear economic values (a_i) of Hazel (1943) in the foundation stocks are obtained by substituting the approximations of [5] and [10] into Equation [20], and rearrangement of the resulting equations.

$$a_{i(PGP)} = .5\,(R'_{MGPF} \times R'_{PF} \times X_i) \quad [21]$$

$$a_{i(MGGPM)} = .5\,(R'_{MGPF} \times Y_i^* \times V'_{BR}) + .25\,(R'_{MGPF} \times R'_{PF} \times X_i) + .5\,(R'_{MGPF} \times X_i^*) \quad [22]$$

$$a_{i(MGGPF)} = (Y_i \times R'_{PF} \times V'_{BR}) + .5\,(R'_{MGPF} \times Y_i^* \times V'_{BR}) + .25\,(R'_{MGPF} \times R'_{PF} \times X_i) + .5\,(R'_{MGPF} \times X_i^*) + (Y_i \times V'_{BS}) + (v_{LH} - c_{LH}) \times Y_i \quad [23]$$

The terms $a_{i(PGP)}$, $a_{i(MGGPM)}$, and $a_{i(MGGPF)}$ are the i^{th} linear economic weights in strains PGP, MGGPM, and MGGPF, respectively. The R'_{MGPF} and V'_{BR} are obtained from Equations [11] and [6]. The R'_{PF} and V'_{BS} are the mean reproductive performance of a PF and the mean productive performance of a broiler sib (sib to PF female). Equations for calculation of R'_{PF} and V'_{BS} are similar to Equations [11] and [6], respectively, but means from the PF population (Table 3) should be used. Also, the equation for calculation of R'_{PF} does not include the .5 coefficient.

The X_i and Y_i are the coefficients of δ_i in the linear approximations for V_{BR} (Equation [5]) and R_{MGPF} (Equation [10]). The X_i^* and Y_i^* are the corresponding coefficients in V_{BS} and R_{PF}. The constant .5 in Equation [21] represents the proportion PGP is of the ancestry of BR. The constants .5 and .25 in Equation [22] represent the proportion MGGPM is of the ancestry of PF and BR, respectively. Constants 1, .5, and .25 in Equation [23] represent the proportion MGGPF is of the ancestry of MGPF, PF, and BR, respectively. Functions for calculating economic values in the foundation stocks and the biometrical relationship between PGP, MGGPM, and MGGPF with the genetic groups in the fundamental production unit are also presented in Table 6.

Equations for estimating the ij^{th} quadratic economic value in Strains PGP, MGGPM, and MGGPF were similar to Equations [21], [22], and [23], but the terms X_i, Y_i^*, Y_i, and X_i^* were replaced by X_{ij}, Y_{ij}^*, Y_{ij}, and X_{ij}^*, respectively. X_{ij}, Y_{ij}^* and Y_{ij} are coefficients of the ij^{th} quadratic term from Equation [4] including products of the broiler performance traits and the economic constants, and the coefficients of the ij^{th} quadratic term from Equation [9] including products of the reproductive traits in PF and MGPF, respectively. For PF, the coefficient .5 was removed from Equation [9]. The term X_{ij}^* is similar to X_{ij}, but means from the PF population are used. It should be noted that the matrix of the quadratic economic weights (A) is symmetric. Thus, in each strain, $A_{ij} = A_{ji}$, and the ij^{th} quadratic economic weight is the sum of $A_{ij} + A_{ji}$ (Wilton *et al.*, 1968). The approximations of the ($A_{ij} + A_{ji}$ elements neglect some of the quadratic terms coming from the products of δ from R and V segments or from between the R segments. Most of the neglected terms are products of δ from different foundation strains. These products may suggest that the value of the genetic improvement in one strain depends on the magnitude of the genetic improvements in

TABLE 6. *Functions for calculating economic weights in the foundation stocks*[1] *from Equations [15] and [16] and the biometrical relationship between PGP, MGGPM, and MGGPF with the genetic groups included in the bioeconomic objective*

PGP	MGGPM	MGGPF	Function[2]	Source in Equations [15] and [16]
.5	.25	.25	$R'_{MGPF} \times R'_{PF} \times X_i$	$R_{MGPF}\,R_{PF}\,V_{BR}$
0	.5	.5	$R'_{MGPF} \times Y^*_i \times V'_{BR}$	$R_{MGPF}\,R_{PF}\,V_{BR}$
0	0	1	$Y_i \times R'_{PF} \times V'_{BR}$	$R_{MGPF}\,R_{PF}\,V_{BR}$
0	.5	.5	$R'_{MGPF} \times X^*_i$	$R_{MGPF}\,V_{BS}$
0	0	1	$Y_i \times V'_{BS}$	$R_{MGPF}\,V_{BS}$
0	0	1	$Y_i \times (v_{LH}-c_{LH})$	$R_{MGPF}\,(v_{LH}-c_{LH})$

[1] PGP = Paternal grandparent, MGGPM = maternal great-grandparent male, MGGPF = maternal great-grandparent female.

[2] MGPF = Maternal grandparent female plus sibs of the opposite sex, PF = two-way cross female parent, BR = three-way cross commercial broiler, X_i and Y_i are the coefficients of δ_i in the linear approximations for V_{BR} (Equation [5] and R_{MGPF} (Equation [10]), X^*_i and Y^*_i are the corresponding coefficients in V_{BS} and R_{PF}.

the other strains. Although this is likely true, incorporation of these terms seemed an unnecessary complication and was ignored.

Phenotypic means in Table 3, and the assumed economic constants, were applied in Equations [21], [22], and [23] to obtain estimates of the quadratic and linear economic weights in the PGP, MGGPM, and MGGPF foundation stocks. The values for rbf, rgf, rlf, blf, glf, and llf in Equation [15] were approximated as \$.50, \$1.69, \$11.36, \$.08, \$1.20, and \$6.24, respectively. It was assumed that MGPF and PF reach 8 lb (8 × 454 g) at the end of a 1-year laying period; the processed carcass constitutes 68% of the live weight and sold for \$.50/lb (454 g); it costs \$.25 to process a cull hen. Numerical estimates for the quadratic and the linear relative economic weights in PGP are presented in Table 7. Similar estimates in MGGPM and MGGPF are presented in Table 8. Estimates are coded by dividing by the economic value of WT in their respective strains. Note that the only difference between Tables 4 and 7 is the coding, because PGP only contributes genetically to the broiler traits and not to the reproduction traits. In PGP, the economic values of the traits other than the broiler traits are zero, as PGP does not influence those traits. A commercial breeder may wish to use his own population means and economic constants with the mathematical equations presented here to derive the relative economic weights that are specifically applicable to his operation.

As reflected by the values in Table 8, in a three-way cross broiler breeding system, reproductive traits are more important in MGGPF than they are in MGGPM. This is because, in such a system, MGGPF influences both MGPF

TABLE 7. *Matrix of quadratic (A) and vector of linear (a) relative economic weights in paternal grandparent (PGP) from quadratic and linear profit functions for the net value of a fundamental production unit in the system.*

	A					
Trait[1]	BLV	WT	DP	BTL	FD	a
BLV	0	.53	3.19	1.71	−.11	1.51
WT	.53	0	.72	.39	0	1.00
DP	3.19	.72	0	2.32	0	5.99
BTL	1.71	.39	2.32	0	0	3.21
FD	−.11	0	0	0	0	−.20

[1] BLV = Broiler livability as proportion, WT = live weight in pounds, DP = dressed carcass as proportion of WT, BTL = breast-thigh-leg as proportion of DP, FD = total unrestricted feed consumption.

TABLE 8. *Matrices of quadratic (A) and vectors of linear (a) relative economic weights in maternal great-grandpanrent male (MGGPM) and maternal-great grandparent female (MGGPF) from quadratic and linear profit functions for the net value of a fundamental production unit in the system*[1]

	A											a	
Trait[2]	BLV	WT	DP	BTL	FD	GLV	LLV	RL	ST	FR	HC	MGGPM	MGGPF
BLV	0	.53	3.19	1.71	−.11	1.60	1.65	2.44	1.58	1.62	1.64	4.48	9.30
WT	.53	0	.72	.39	0	0	0	0	0	0	0	1.00	1.00
DP	3.19	.72	0	2.32	0	0	0	0	0	0	0	5.99	5.99
BTL	1.71	.39	2.32	0	0	0	0	0	0	0	0	3.21	3.21
FD	−.11	0	0	0	0	0	0	0	0	0	0	−.20	−.20
GLV	4.22	0	0	0	0	0	1.67	2.46	1.60	1.63	1.63	3.00	7.88
LLV	4.36	0	0	0	0	4.41	0	2.55	1.65	1.69	1.69	3.10	8.15
RL	6.46	0	0	0	0	6.53	6.75	0	2.44	2.49	2.49	4.58	12.06
ST	4.18	0	0	0	0	4.22	4.36	6.46	0	1.62	1.62	2.97	7.80
FR	4.27	0	0	0	0	4.32	4.46	6.60	4.27	0	1.65	3.04	7.97
HC	4.27	0	0	0	0	4.32	4.46	6.60	4.27	4.38	0	3.04	7.97

[1] The upper and the lower diagonal of the A matrix represent the upper or the lower diagonal of the symmetric matrices of quadratic relative economic values for MGGPM and MGGPF, respectively, as defined by Wilton *et al.* (1968).

[2] BLV = Broiler livability as proportion, WT = live weight in pounds, DP = dressed carcass as proportion of WT, BTL = breast-thigh-leg as proportion of DP, FD = total unrestricted feed consumption, GLV = grower livability as proportion, LLV = layer livability as a proportion, RL = rate of lay in hen-day proportion, ST = settability as proportion of RL, FR = fertility as proportion of ST, HC = hatchability as proportion of FR.

and PF, whereas MGGPM influences only PF. If the individual commercial broilers are profitable, the more commercial crossbred progenies that are produced from each such cycle, the more profitable the total integrated system will be. The MGGPM is used as the maternal male stock. Therefore, even though MGGPM contributes genetically to the reproductive potential of PF through MGPM, the number of chicks produced by each MGPM does not play a significant role in the bioeconomic efficiency of the system.

REFERENCES

Andrus, D. F., and L. D. McGilliard, 1975. Selection of dairy cattle for overall excellence. J. Dairy Sci. 58:1876–1879.

Becker, W. A., 1975. Manual of Quantitative Genetics. 3rd ed. Washington State University Press, Pullman, WA.

Dickerson, G., 1970. Efficiency of animal production – Modeling the biological components. J. Anim. Sci. 30:849–859.

Fisher, R. A., 1936. The use of multiple measurements in taxonomic problems. Ann. Eugen. 7:179–189.

Harris, D. L., 1970. Breeding for efficiency in livestock production: Defining the economic objectives. J. Anim. Sci. 30:860–865.

Harris, D. L., M. K. Akbar, and C. R. Arboleda, 1985. System simulation for designing integrated broiler breeding programs. *In* Proc. 34th Annu. Natl. Breeders Roundtable. St. Louis, MO.

Harris, D. L., T. S. Stewart, and C. R. Arboleda, 1984. Animal Breeding Programs: A Systematic Approach to Their Design. Advances in Agricultural Technology. USDA-ARS.

Hazel, L. N., 1943. The genetic basis for constructing selection indices. Genetics 28:476–490.

Hogesett, M. L., Jr., and A. W. Nordskog, 1958. Genetic-economic value in selection for egg production rate, body weight and egg weight. Poultry Sci. 37:1404–1419.

Kinney, T. B., Jr., 1969. A Summary of Reported Estimates of Heritabilities and of Genetic and Phenotypic Correlations for Traits of Chickens. Agriculture Handbook No. 363. ARS-USDA, Washington, DC.

Moav, R., and J. Moav, 1966. Profit in a broiler enterprise as a function of egg production of parent stocks and growth rate of their progeny. Br. Poult. Sci. 7:5–15.

Newman, S., D. L. Harris, and D. P. Doolittle, 1985. Economic efficiency of lean tissue production through crossbreeding: Systems modeling with mice. I. Definition of the bioeconomic objective. J. Anim. Sci. 60:385–394.

Smith, H. F., 1936. A discriminant function for plant selection. Ann. Eugen. 7:240–250.

Strain, J. H., and A. W. Nordskog, 1962. Genetic aspects of the profit equation in a broiler enterprise. Poultry Sci. 41:1892–1902.

Wilton, J. W., D. A. Evans, and L. D. Van Vleck, 1968. Selection indices for quadratic models of total merit. Biometrics 24:937–949.